

How can large entropy be produced so early at RHIC?

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- Hydro description works extremely well,
[including rather peripheral ($B \sim 10 \text{ fm}$) ellipticity
and large $P_{\perp} \sim 2 \div 3 \text{ GeV}$ → nothing like that at SPS]

! EOS which fits best agrees with lattice!

- Estimates of early parton density (Gyulassy, Wang)
from: (i) "jet quenching" → $\pi^0(p_{\perp} > 3 \text{ GeV, central})$
(ii) $v_2(p_{\perp} > 2 \text{ GeV})$

give

$$\frac{dN_q}{dy} \sim 1000$$

Much more than
pQCD, HIJING...

← Close to observed
or "late" →

$$\frac{dN_{\pi}}{dy} \sim 1000$$

"Early"

Supports nearly adiabatic expansion!

Like in Big Bang

- New non-perturbative mechanism of parton-parton collisions, the so called instanton/sphaleron mechanism may produce it!

Developed recently for explanation
of soft Pomeron

without connection to heavy ions...

| Khazeev, Kovchegov, Levin
Shuryak, Zakharov ...

Heavy ion RHIC ES hep-ph/0101269

from
D. Teaney, J. Lauret, E. Shuryak
PRL 86 (2001) 4783

See also
Kopch, Huovinen, Heinz, Heiselberg
PL B500 (2001) 232

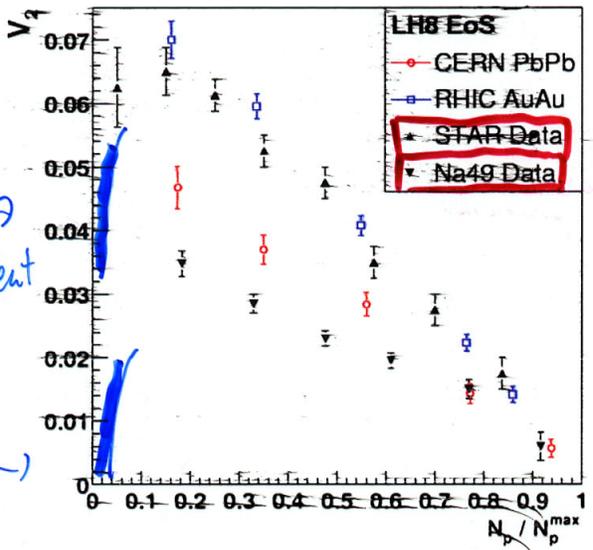
How good is hydro?

U.S. "few scattering model"

At RHIC deviation from hydro
only for very peripheral, $N_p / N_p^{max} < 0.1$

Heiselberg et al

at SPS start
at ~ 0.6



where is the transparent region?

Heiselberg...

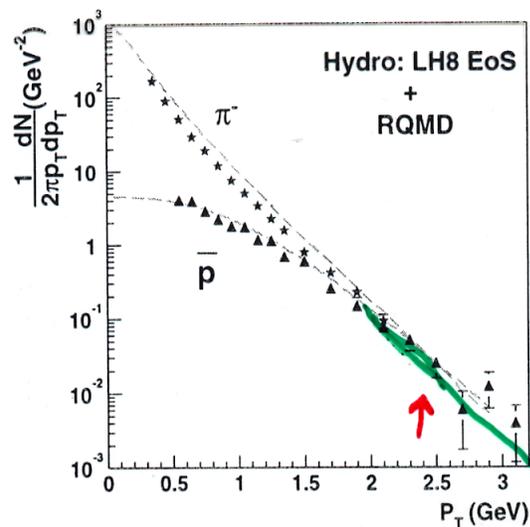
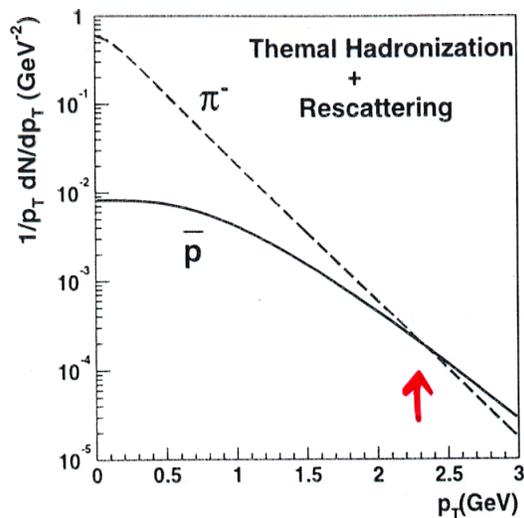
hydro:
 $v_2 \sim \epsilon \sim (N_p - N_p^{max})$

small density limit:

$v_2 \sim N_p$

not seen

Figure 3: v_2 versus impact parameter b , described experimentally by the number of participant nucleons, for RHIC STAR and SPS NA49 experiments. Both are compared to our results, for EoS LH8.



- Radial flow increases p, \bar{p} slopes as compared to π ones \rightarrow crossing

$\Rightarrow \bar{p}/\pi^-$ ratio exceed 1 for $p_{\perp} > 2$ GeV (never seen before...)

[fig. a demonstrate it with simple blast model $v_{\perp} \approx 0.6$]

[fig. b is H2H model (absolutely normalized predictions) vs PHENIX data]

- At $p_{\perp} \rightarrow \infty$ slopes become the same "blue shifted"
 $"T" = T \sqrt{\frac{1+v_{\perp}}{1-v_{\perp}}} \approx 2T$ there "thermal ratio" $\frac{\bar{p}}{\pi^-} \rightarrow 2$ (spins)

- Hard processes (jet or minijet fragment.) predict $\bar{p}/\pi^- \approx 0.1 \div 0.3 \ll 1$

(One more argument that jets are quenched!)

No power-like tail?

Jet quenching!



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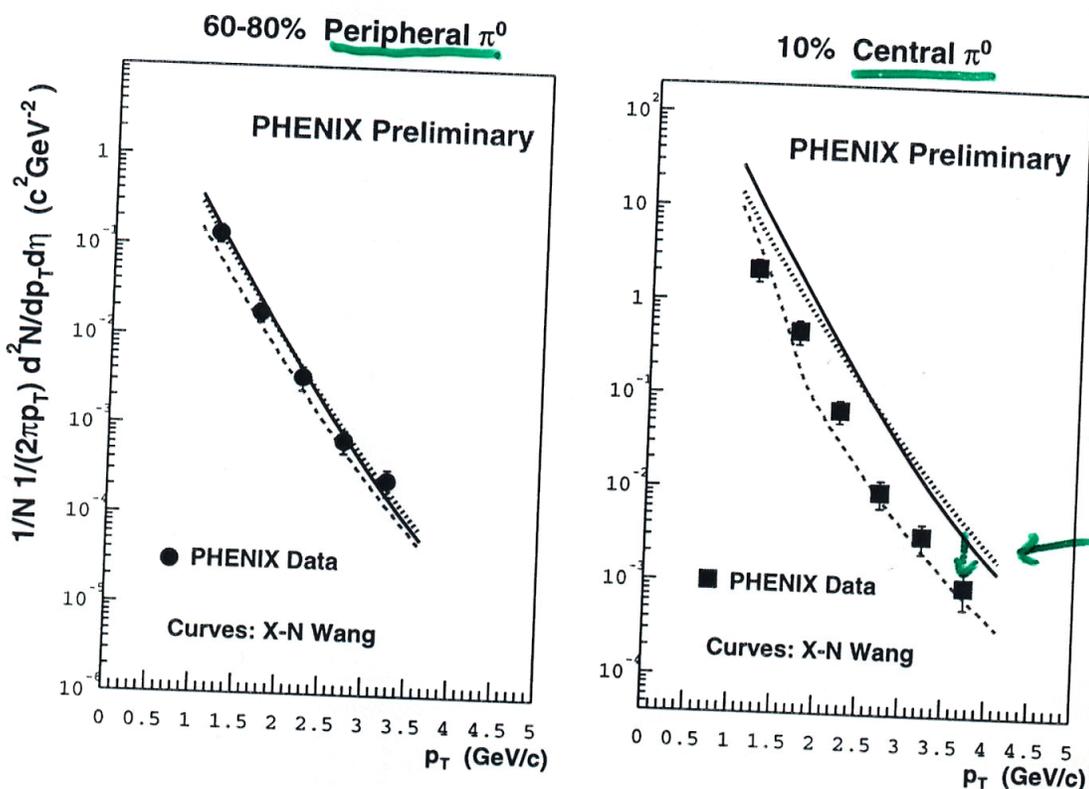


Figure 3. Comparison of PHENIX π^0 spectra to theoretical calculations under three scenarios and for two centralities. The points are the same as on Figure 1. The curves are calculations of X-N. Wang [1]. Solid lines are a pQCD calculation for pp scaled by the mean number of binary collisions. The dotted lines add shadowing and p_T broadening. The dashed lines add a $dE/dx = 0.25$ GeV/fm parton energy loss.

- Guylassy et al: such suppression means $\frac{L}{\lambda} \approx 3$ or $\frac{dN_g}{dy} \approx 1000$ (AuAu Central)
- Independent study of $v_2(p_T > 2 \text{ GeV})$ give the

Gyulassy, Vitev, Wang
nucl-th 10012092

Star data

favor
 $\frac{dN^s}{dy} \approx 1000 !!$

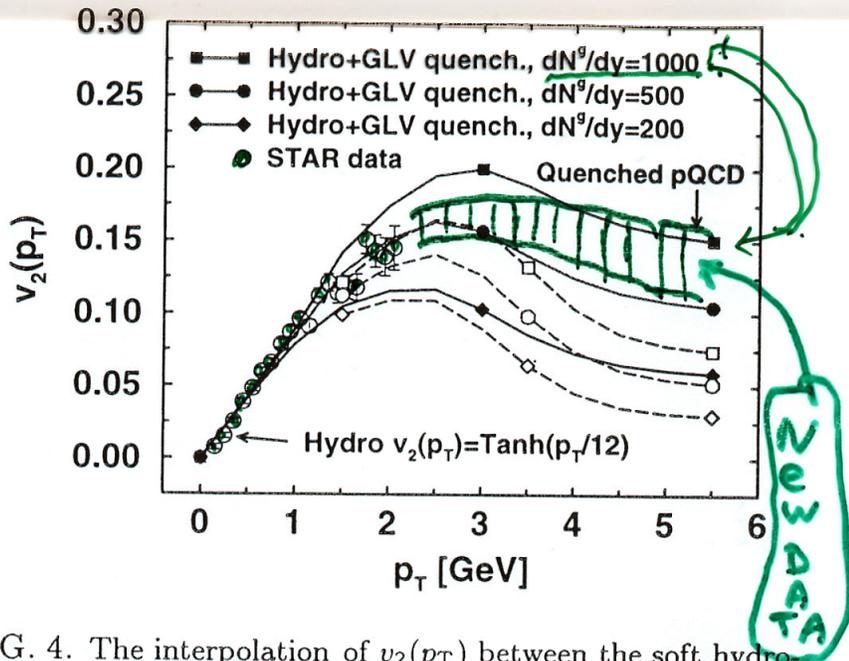


FIG. 4. The interpolation of $v_2(p_T)$ between the soft hydrodynamic [12] and hard pQCD regimes is shown for $b = 7$ fm. Solid (dashed) curves correspond to cylindrical (Wood-Saxon) geometries.

HIJING $\rightarrow 200$
(= pert. partonic reactions, $P_{\text{cutoff}}^2 \sim 20 \text{ GeV}^2$)

$\frac{dN^{\pi}}{dy} \approx 1000$ also

Conclusion

Like in the Big Bang,
in the little one
the whole entropy is there
even at earliest time we
can measure it!

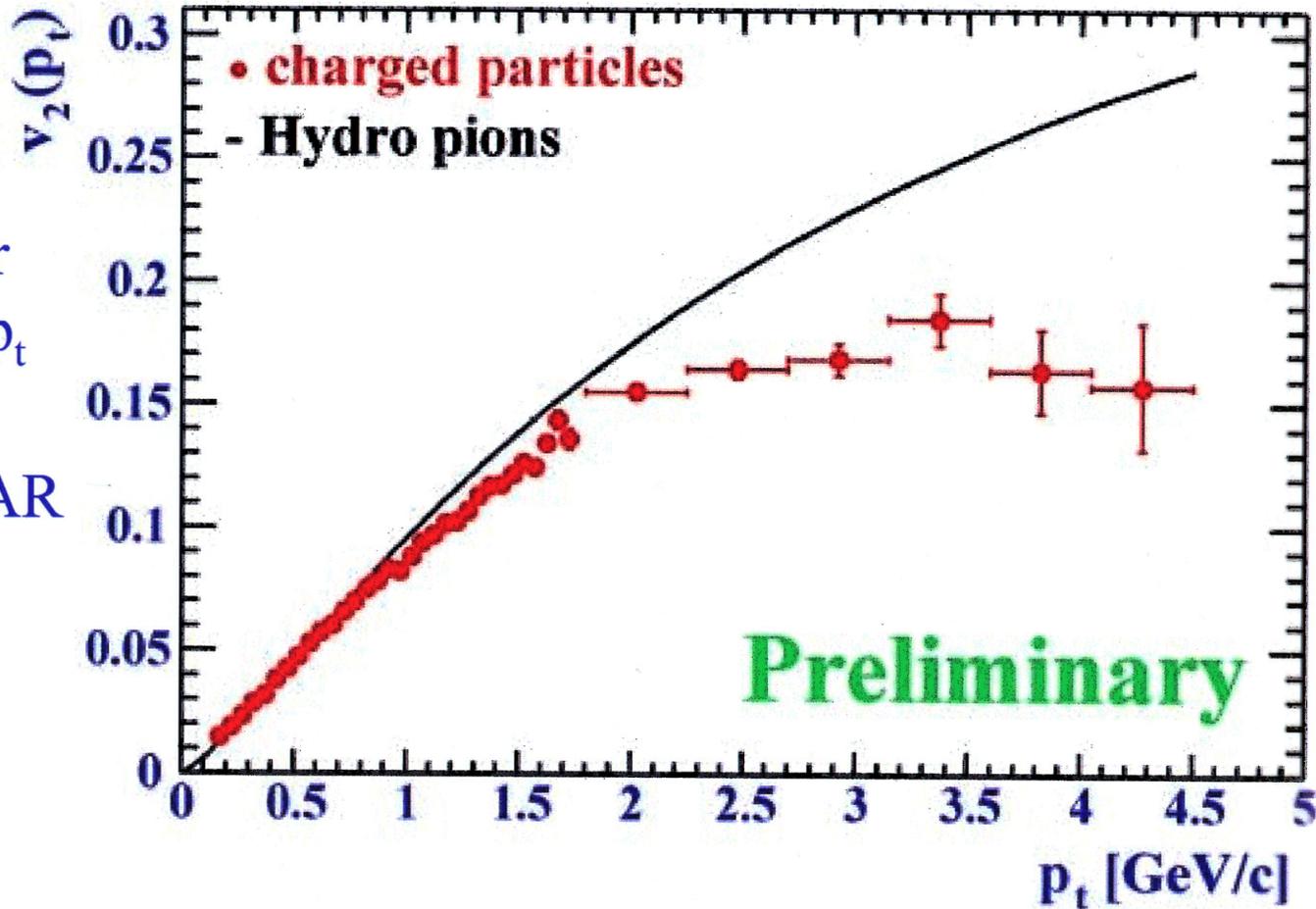
1?

Charged particle anisotropy

$$0 < p_t < 4.5 \text{ GeV}/c$$

STAR

Only statistical errors
Systematic error
10% - 20% for p_t
 $= 2 - 4.5 \text{ GeV}/c$
More in the STAR
high-pt talk
(James Dunlop,
PS2, this
afternoon)



- Why ^{does} the cross section grow?
 $\sigma \sim s^{(d-1)}$ Pomeron Regge pole \rightarrow not so high s

$$\sigma = \underbrace{\sigma_0}_{\pi r_*^2} \left[1 + (\Delta(0) + \alpha' \ln s) \ln s + \dots \right]$$

grows

The part which is constant with s
 $\sigma_0 \approx \frac{1}{9} \sigma_{NN} \Rightarrow r_* = \frac{1}{3} r_{NN}$

$\Delta(0) \approx 0.08$ "Pomeron intercept"
with $\alpha' = 0.15$ with $\alpha' = 0.15$ with $\alpha' = 0.15$
 (Laudshoff et al)
 $\alpha' \approx 0.25 \text{ GeV}^{-2}$

- Why $\Delta(0)$ is so small?

$$\Delta(0) \approx \frac{\#}{O(1)} \left(\frac{\pi^2 u g^4}{0.06} \right)$$

instanton diluteness
 current calculation
 (ES + I. Faldt, in progress)
 $\Delta(0) \approx 0.12$

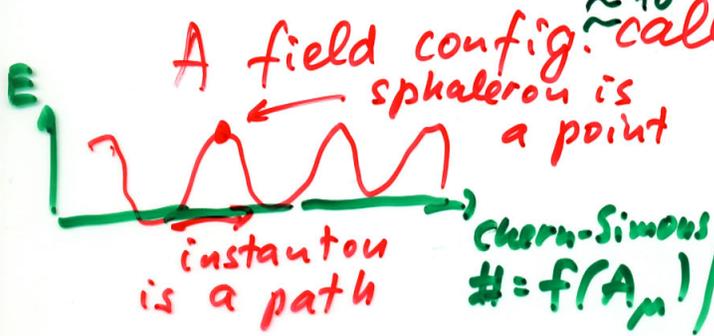
- Why α' is so ~~large~~ ^{small}?

$$\alpha' = \frac{1}{(26 \text{ GeV})^2} = (0.1 \text{ fm})^2$$

Because instantons are small!

current estimate $\alpha' \approx \frac{0.5}{\text{GeV}^2}$

- What is produced in the process?



$$E_{\text{sph}} \approx \frac{3\pi^2}{g^2} \approx 25 \text{ GeV}$$

Klinkhammer Manton

Basically a set of glueballs (if zero color but not necessarily so...)

- No odderon!

Instanton is $SU(2)$ object
 Odderon requires abc in $SU(3)$

Instanton/sphaleron mechanism

Sounds complicated, but the main physics is easy to understand...

Developed in electroweak theory in early 90's

Ringwald, McLerran, Zakharov, Khase, Diakonov

recently used for QCD Kharzeev, Kouchegov, Levin Shuryak, Zahed...

The instanton vacuum ES82



$\langle \bar{q}q \rangle \neq 0, \sim 2/fm^3$
each flavor

→ Quark gets a mass $\Rightarrow \sim 400MeV$
"constituent" quarks

→ Quarks gets a sea, which is polarized in flavor and spin in opposite direction

High energy collision leads to sublimation of all this structure instantly



→ Instantons (which are virtual objects used to describe tunneling)
↓
Sphalerons → Real Balls of magnetic glue which then explode

→ Condensed quarks get real too!

Quantum mechanics of it is like this:

Vacuum



Collision, step 1

$\tau \sim 1/\sqrt{s}$

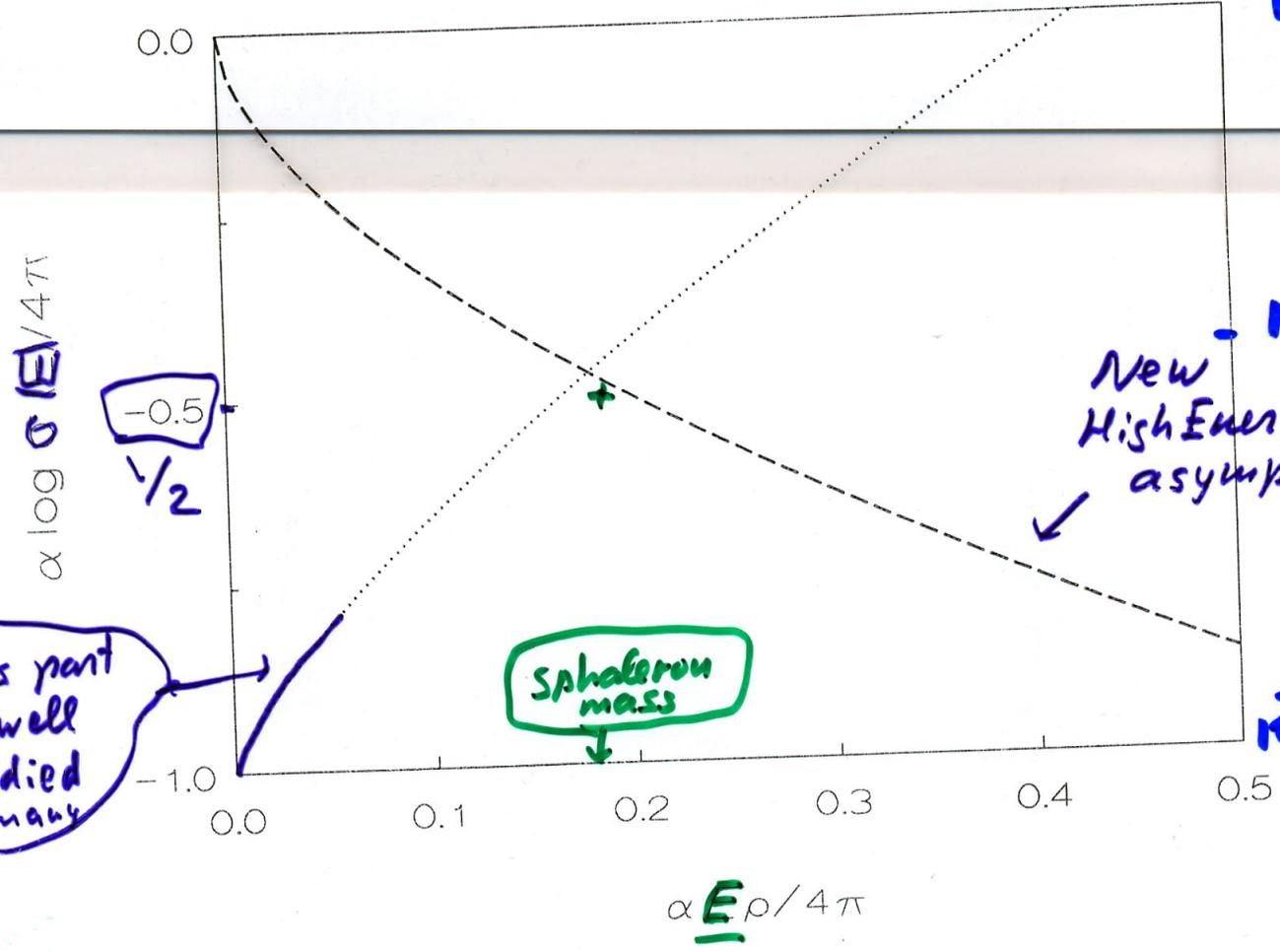
System is rapidly localized, wherever it is
The maximal cross section falls on sphaleron

Collision step 2

$\tau \sim g$

Sphalerons rolls downhill \Rightarrow gluons + quarks

QCD EW
1



This part is well studied by many

New High Energy asymptotics

Sphaleron mass

-0.5
1/2

10^{-2}
 10^{-85}
 10^{-4}
 10^{-80}

D. Diakonov, V. Petrov → arXiv:hep-th/9307356 28 Jul 1993

$\sim \frac{1}{N} \frac{dE}{dE}$ E is the gg (actually WW) energy

using a different path in the ~~space~~ space of all configurations...

Instanton/sphaleron mechanism @ RHIC?

E.S. hep-ph/0101269
PLB, in press

● Partonic production mechanism

pions participant \rightarrow S Photos
B-dependence

$$M_{(b)} = \left(\frac{1-x}{2}\right) N_{part}(B) + x N_{coll}(B)$$

(Kharzeev, Nardi)

$$x = 0.05 \pm 0.03 \quad \sqrt{s} = 56 \leftarrow$$

$$0.09 \pm 0.03 \quad 130$$

Part of PP which scales differently

● Can be identified with "growing part" of σ_{pp} leading to "prompt production" of some "objects" \leftarrow ES



$$\frac{d\sigma_{objects}}{dy}$$

parton-parton

$$\sim \frac{few}{1000} fm^2 \text{ (rare process)}$$

● And still, in central AuAu $\frac{dN_{objects}}{dy} \sim 100$ are produced

● What are these "objects"?

Minijets?

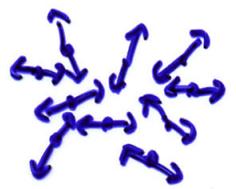
$$gg \rightarrow \text{"objects"} \rightarrow gg$$

we discuss $p_t \sim 1 \div 2$ GeV here! Cutoff unknown...

large angle

$$\rightarrow \frac{dN_g}{dy} \sim 200 \text{ (as HIJING predicted)}$$

\rightarrow little rescattering, no v_2 no jet quenching

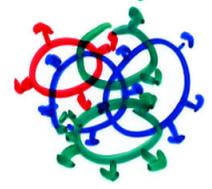


\rightarrow x early time picture

Sphalerons?

\rightarrow Unlike minijets, they are classically unstable and explode into spherical way into ~ 4 gluons

\rightarrow in QGP there are no condens. so $\bar{u}u, \bar{d}d$ (ES) jump out



same σ , E_T but much more entropy...

"Ready to fall"

Sphaleron: mass and decay

• Magnetic object $\vec{B}(r)$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{B} = 0$$

$B_i \sim \delta_{ij}$: hedgehog, like monopole
But no magnetic charge

$$A_i \sim \epsilon^{aim} r^m f$$

(Klinkhamer, Manton) ¹⁹⁸⁴ in electroweak theory
 $M \sim 14 \text{ TeV}$, in $\lambda \rightarrow \infty$ limit Higgs decouples

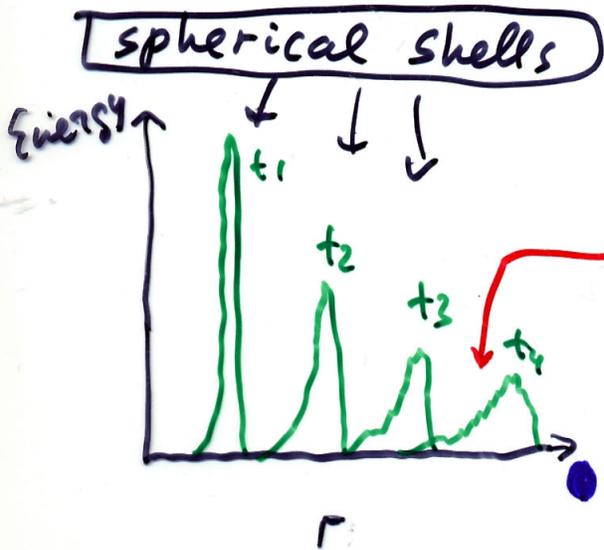
$$M \approx \frac{30}{g^2 \rho} \sim 2.5 \text{ GeV in QCD, if } \rho = 1/3 \text{ fm}$$

• Decay

J. Zadozay, PL, 1992 for EW
G. Garter + ES \rightarrow in progress for QCD



Recall that in $A_0 = 0$ gauge
 $\vec{E} = \frac{\partial \vec{A}}{\partial t}$
 \uparrow
momentum
(but \vec{E}^2 is gauge inv.)



triples are not my shaky hand
But a trace of e^{ikr}
momentum $k \rightarrow \text{const}$
 $r \rightarrow \infty$

$|C_k|^2$ occupation numbers $\rightarrow \text{const}$

EW sphalerons $\rightarrow \sim 50$ W+Z
about 200 GeV each

QCD sphalerons $\rightarrow \sim 5-7$ gluons
 $\sim 500 \text{ GeV}$ each

Puzzle:



Phenomenological Summary

Mini-jets vs Instanton-induced Clusters

In hh'

→ Both can explain growth of $\sigma(s)$, multiplicity size

→ Mini-jets can be looked for as clusters in (θ, φ) statistically ...

→ Instanton-induced clusters, $M = 2.5 - 3$ GeV, isotropic $\Delta y \sim 1$, but $\Delta \varphi = 2\pi$

→ Mini-jets are expected to fragment as string fragm.
 → Standard $\lambda_{HBT} \approx 0.5$ and standard $\eta/\pi, \eta'/\pi, K/\pi$

→ Enhanced η', η, K , λ_{HBT} decreases, as observed!
 in pp at large multiplicity

In AuAu etc

→ Both can explain multiplicity growth, and why there appears new component at RHIC $\sim N_{coll}(B)$ (instead of $\sim N_{part}(B)$)

→ Mini-jets with a cutoff from pp fit (HIJING) lead to $\frac{dN}{dy} \sim 200$ mini-jets (central AuAu at RHIC)

It is not enough for collective effects and jet quenching

Lower the cutoff? Higher order processes?

→ Instanton-induced reactions (into QGP, no hadrons) with similar cross section

leads to: much higher entropy!

and may solve quark production problem

